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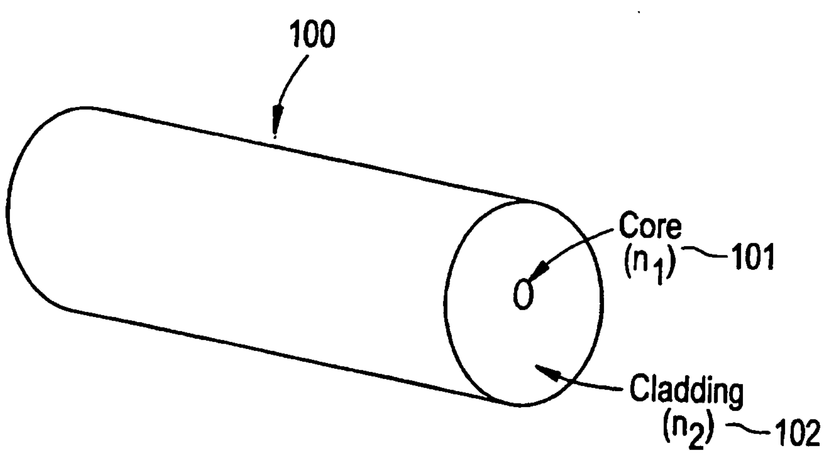

(57) Abstract: Single mode optical fiber waveguides are disclosed that offer a broader band for transmission over the wavelength range of about 1300 nm to about 1700 nm with reduced bending loss. The extended ranges of these fibers are achieved by altering the optical characteristics of the fiber, namely, the MAC number, the mode field diameter ("MFD"), and the cut-off wavelength. The single mode fibers disclosed exhibit a lower MFD and higher cut-off wavelength as a result of altering the MAC number of the optical fiber waveguide. In addition, optical fiber transmission systems, wave division multiplexing ("WDM") systems, and optical fiber ribbon cables are disclosed that incorporate the single mode optical fiber of the present invention.

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HIGHER WAVELENGTH OPTIMIZED OPTICAL FIBER WAVEGUIDE

This application claims the benefit of U.S. Provisional Application No. 60/159,075, filed October 12, 1999.

FIELD OF THE INVENTION

The present invention relates to a single mode optical fiber waveguide suitable for transmitting an optical signal within an operating window of about 1300 nanometers ("nm") to 1700 nm with minimal bending loss. Other embodiments of the proposed invention include a optical fiber ribbon cable and telecommunication systems which utilize the single mode optical fiber waveguide of the present invention.

BACKGROUND OF THE INVENTION

Optical fiber waveguides, or simply optical fibers, are well known in the art. There are two main optical fiber types: single mode and multimode. Single mode fibers differ from multimode fibers in many ways. For example, single mode fibers have a central core region that is significantly smaller in diameter than that of multimode fibers. This difference in diameter imparts many properties. Single-mode fibers are preferred in long-distance communication systems because they allow information to be transmitted at higher rates, over greater distances, without the need for signal repeaters. Further, single mode fibers have a bandwidth that is much greater than multimode fibers and can transmit optical signals at greater speeds.

A critical area to control in either single mode or multimode optical fibers is attenuation. Attenuation is the decrease in magnitude of the optical signal power as it is transmitted between two points. The attenuation loss overcomes the optical signal power as it propagates until the signal is lost in the noise at the receiver. For optical fibers, the attenuation loss is measured in decibels per kilometer (dB/km) at a specific wavelength. The lower the attenuation is, the better optical transmission qualities the fiber has.

Optical signals or light pulses travel as electromagnetic waves within the single mode optical fiber waveguide. These signals propagate through the fiber at certain wavelengths in pathways known as modes. Each mode has two polarizations associated with it and is described as being doubly degenerate. A key parameter that describes the mode structure is a dimensionless parameter known as the normalized frequency, V-parameter, or simply, the V value. For a typical step index profile optical fiber, the V value is defined by:

$$V = [(2 * \pi * a) / \lambda] * \sqrt{n_1^2 - n_2^2}$$

where: a is the radius of the core of the fiber;

λ is the nominal free-space wavelength of light;

n_1 is the refractive index of the core; and

n_2 is the refractive index of the cladding.

The V value determines the number of electromagnetic modes in the fiber. The number of modes present in an optical fiber is directly related to the V value. Thus, the V value increases as the number of modes that the optical fiber can accommodate increases. A more detailed discussion of the V value is found in Chapter 2 of John Powers, An Introduction to Fiber Optic Systems (1997) or Section 2.3.6 of John M. Senior, Optical Fiber Communications: Principles and Practice (1985) which are incorporated in their entirety herein by reference.

A step-index profile, single mode fiber has a V value generally between about 2 and about 2.405. Optical fibers with refractive index profiles which differ from the step-index profile will exhibit slightly different V values and properties. Multimode fibers, by contrast, have V values greater than 2.405. To achieve a relatively lower V

value, the core radius and refractive index difference between the core and the cladding should be kept relatively low. However, if the V value is too low, a considerable amount of the mode's transmitted power will be found in the fiber's cladding and not the central core. For example, fibers with V values of 1.4 or less propagate 50% of their electromagnetic radiation through the cladding. This is problematic because the cladding power can be readily lost through optical fiber coating losses, bending losses, splicing and other mechanisms.

Single mode fibers are designed to propogate the fundamental mode of a particular wavelength. The minimum wavelength at which an optical fiber will support only one propagating mode is referred to as the cutoff wavelength. If the system operating wavelength is below the cutoff wavelength, multimode operation may take place and the introduction of an additional source of dispersion may limit a fiber's information carrying capacity.

The physical deployment of the fiber plays an important role in defining the region of single-mode operation. Cabling of the optical fiber will typically shift the measured fiber cutoff wavelength to shorter wavelengths. Therefore, the cabled cutoff wavelength can be of more interest to the user because it's a more accurate representation of the cutoff wavelength that can be expected in actual use.

An additional parameter of interest is dispersion. Dispersion is the source of bandwidth limitations in an optical fiber. Dispersion relates to the spread or increase in width of a light pulse as it propagates along the length of the fiber. In single mode fibers, total dispersion is primarily effected by the material dispersion and waveguide dispersion. Material dispersion is caused by the differential delay of various wavelengths of light in the waveguide material. Waveguide dispersion is attributed to light pulses traveling in both the core and the cladding of the fiber. Both of these dispersion sources are generally influenced by the interdependence of the refractive index of the core and cladding material on wavelength. However, both types of dispersion are viewed separately and can have a cumulative effect on the transmission properties of the optical fiber.

Single mode fibers of the prior art are generally operated at wavelengths ranging from about 1310 nm to 1550 nm. To minimize the total dispersion of a single mode fiber, it is desirable to operate at a wavelengths longer than about 1270 nm. At a

wavelength of approximately 1300 nm, the small positive material dispersion cancels out the small negative wavelength dispersion causing a net dispersion of zero for high silica content optical fibers. The upper range of the operating range, around 1550 nm, is preferred, however, to keep the attenuation loss of the optical fiber low for many reasons. Optical fibers exhibit a hydroxyl peak at around 1380 nm due to the introduction of water which appear as hydroxyl (-OH) groups during the manufacturing process. The hydroxyl peak is a significant source of attenuation for an optical fiber. Further, the theoretical minimum loss for glass fiber, 0.16 dB/km, occurs at a wavelength of 1550 nm.

One solution, to minimize total dispersion and attenuation loss in an optical fiber, is to shift the dispersion to wavelengths around 1550 nm. Optical fibers which are designed for operation at wavelengths around 1550 nm are called dispersion shifted fibers. In dispersion shifted fibers, the zero of total dispersion lies between 1330 nm to 1620 nm rather than at 1300 nm. Conventional methods to shift the zero dispersion above 1300 nm include lowering the V value for the fiber, altering the refractive index profile of the fiber, and/or doping of the core of the fiber with germanium oxide (GeO_2) or other additives. U.S. Pat. No. 4,715,679, issued to Bhagavatula, assigned to the owner of the present invention, and incorporated herein by reference in its entirety, discloses a method to shift the dispersion of a single mode optical fiber by altering the refractive index profile of the fiber.

Increasing the operating wavelength to around 1550 nm to minimize total dispersion and attenuation loss is challenging. These two objectives, unfortunately, compete against one other. Waveguide dispersion is very sensitive to changes in the optical fiber parameters. As mentioned earlier, lowering the V value to about 1.5 may cause more of the light pulse to propagate through the cladding than through the central core region. This would have a negative impact on waveguide dispersion. In addition, waveguide dispersion is also influenced by the diameter of the central core region, the refractive index profile and the fractional change delta ("Δ" expressed as $\Delta = (n_1^2 - n_2^2)/2*n_1^2 \approx (n_1 - n_2))$ of the refractive indices of the central core region (n_1) and the cladding (n_2) of the optical fiber. A decrease in the core region diameter would require a doubling of the Δ to keep the V value constant. Material dispersion, on the other hand, is principally effected by doping of the central core region.

Single mode fibers of the prior art are generally operated at wavelengths which range between about 1310 nm and 1550 nm. While the lower limit of the range may be preferred to minimize total dispersion, the water or hydroxyl peak at 1380 nm is a major source of attenuation loss for a fiber. Thus, the upper limit of this range is generally preferred to keep the attenuation of the optical fiber low. Even fibers that have lowered, or eliminated, the hydroxyl peak at 1380 nm experience losses due to Rayleigh scattering. In addition, as the wavelength of the fiber is increased, more of the optical signal is propagated in the cladding area rather than in the central core region. This creates a major source of attenuation loss for single mode optical fibers, known as bending loss, when the optical fiber is cabled or bent. Eventually, the fundamental propagating mode LP_{01} becomes lossy. The present invention fulfills the need for a novel single mode waveguide fiber that has an extended operating range beyond 1550 nm by maintaining low bending loss at acceptable performance levels.

Optical fibers are generally cabled into a co-planar bundle of fibers, encapsulated into a ribbon cable matrix or other means, and then incorporated into a transmission system. An optical fiber transmission system typically consists of the signal to be transmitted, a source, a detector, the optical fiber cable, connectors and splices, and signal repeaters and amplifiers. Transmission system components that can support higher operating wavelength ranges, such as laser sources that can transmit a light pulse at wavelengths around 1550 nm or above, are in common usage.

Single mode optical fibers are particularly suited for a transmission system known as wavelength division multiplexing ("WDM") systems. WDM are high data rate systems that allow simultaneous transmission of several signals in an optical waveguide at differing wavelengths. These systems usually include a source that can send signals at multiple wavelengths or input channels, a multiplexer, an optical fiber cable, a demultiplexer, and multiple output sources or output channels. U.S. Pat. No. 5,483,612, issued to Gallagher et al., assigned to the owner of the present invention, and incorporated herein by reference, discloses a typical WDM system. Present WDM systems separate the wavelengths of the input channels by about 1 - 10 nm. Finer wavelength separations can allow for more optical signals to be transmitted along the length of the optical fiber but can also create cross-talk problems. Additionally, single mode optical fibers of the prior art are ill-suited to meet the demands of a WDM system

due to the difficulties in minimizing total dispersion and attenuation loss, particularly in the higher wavelength ranges. The single mode optical fiber once cabled is suitable for WDM systems because it can accommodate a greater number of wavelengths in the upper end of its operating range.

SUMMARY OF THE PRESENT INVENTION

One aspect of the present invention relates to a single mode optical fiber capable of operating in wavelengths between about 1300 nm and about 1700 nm with minimal loss, said fiber comprising a MAC number, measured at 1625 nm, which is equal to or less than about 7.8, more preferably equal to or less than 7.6. The MAC number, as used herein, is the Mode Field Diameter (MFD) in microns divided by the fiber cut-off wavelength in nanometers and multiplied by a factor of 1000. In single mode optical fibers, the Mode Field Diameter ("MFD") is slightly larger than the core region diameter and represents the effective diameter of the light mode propagating through the fiber. A low MAC number can be influential in minimizing the bending loss of an optical fiber. Excess losses occur at bends along the fiber path because the geometry of the core and cladding interface changes and due to stress induced index changes. As a result of this change, some of the guided light that is propagated through the fiber is transmitted from the core into the cladding. The susceptibility of a fiber to these losses is directly dependent upon the MAC number, and therefore, MFD, and cut-off wavelength. Single mode optical fibers have been made according to the invention which exhibit micro-bending loss which is less than 0.7 dB/m, and more preferably less than 0.48 dB/m at 1700 nm, and less than 0.49 dB/m at 1550 nm, more preferably less than 0.35 dB/m at 1550 nm. The single mode fiber of the present invention thus achieves lower bending loss by lowering the MAC number.

Preferred fibers in accordance with the invention exhibit a mode field diameter of 8.6 μm or less at a wavelength of 1310 nm and a cabled cut-off wavelength which is at most about 1330 nm. These fibers also exhibit a loss which is attributable to micro-bending is less than 0.35 dB/m at 1550 nm, and less than .7 dB/m at 1700 nm, more preferably less than .5 dB/m at 1700 nm. The loss due to macro-bending (one turn around a 20 mm mandrel) is preferably less than 2 dB/m at 1550 nm, more preferably less than 0.7 dB/m at 1550 nm, and less than 11 dB/m at 1700 nm.

Other embodiments of the present invention are ribbon cables, transmission systems, and WDM systems which incorporate the single mode optical fiber of the present invention. These systems are unique because they allow the user to exploit operating wavelengths in the region of about 1300 nm to about 1700 nm - a range previously deemed substantially unusable due to unacceptable bending losses.

A more complete understanding of the present invention, as well as further features and advantages of the invention will be apparent from the following Detailed Description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a typical single mode, optical fiber waveguide.

Figure 2 illustrates the fractional change delta in refractive index versus fiber radius for three single mode optical fibers in accordance with the present invention.

Figure 3 illustrates the averaged micro-bending loss in db/m vs. wavelength for single mode optical fibers of the present invention compared with single mode optical fibers of the prior art under lateral load conditions.

Figure 4 illustrates the averaged attenuation value of several fibers with similar MAC numbers versus wavelength of various single mode fibers compared against the single mode, optical fiber waveguide of the present invention under loose coil conditions.

Figure 5 illustrates the averaged macro-bending loss in db/m vs. wavelength for single mode optical fibers of the present invention compared with single mode optical fibers of the prior art subject to 1 mandrel turn at 20 mm.

Figure 6 illustrates a typical optical fiber ribbon cable.

Figure 7 provides an example of an optical transmission system.

Figure 8 provides an example of a WDM system.

DETAILED DESCRIPTION

The present invention relates to a single mode optical fiber that operates at a wavelength range between about 1300 to about 1700 nm while minimizing bending loss to acceptable performance levels. Novel optical ribbon cables, transmission systems, and WDM systems that utilize the single mode optical fiber of the present

invention are also disclosed.

Production of the optical fiber of the present invention can be effected by standard methods. In brief, the process involves fabricating the core and cladding layer to become a preform, heating the preform to draw an optical fiber therefrom, coating the cladding layer with a primary polymeric coating material, optionally coating the primary polymeric coating material with a secondary polymeric coating material, and optionally depositing an ink coating around the secondary coating material. If the optical fibers are cabled into a ribbon, the process further includes arranging a plurality of the coated optical fibers in a coplanar configuration, and applying a ribbon matrix material to the fibers so that the planar arrangement is thereafter maintained.

The core and cladding layer are typically produced from a preform in a single or two step operation by methods which are well known in the art. The optical fibers of the present invention are drawn from a glass preform. In the preferred embodiment of the present invention, the glass preform is a soot preform made by a chemical vapor deposition process. Fabrication of soot preforms through chemical vapor deposition processes is well-known in the art. Some examples of such processes are the outside vapor-phase process ("OVD"), the modified chemical vapor deposition process ("MCVD"), the plasma-activated chemical vapor deposition process ("PCVD"), or the vapor axial deposition process ("VAD"). A more detailed discussion of these processes is provided in Kirk-Othmer Concise Encyclopedia of Chemical Technology, (Jacqueline I. Kroschwitz ed., 4th ed. 1999), pp. 824-827 or John M. Senior, Optical Fiber Communications Principle and Practice (1985), pp. 118 - 127 which are incorporated herein by reference. One method to practice the present invention is the OVD process such as the method disclosed in U. S. Pat. No. 4,453,961 issued to Berkey, which is assigned to the assignee of the present invention and incorporated by reference in its entirety herein. However, it is understood that the present invention is applicable to other CVD or glass preform fabrication processes.

After the optical fiber is drawn from the preform, the optical fiber is coated with one or more polymer coatings for added protection. The Berkey '961 patent discloses an optical fiber that has a primary coating, a secondary coating, and an ink coating that is adjacent to and surrounding the cladding layer.

It is well known to draw glassy optical fibers from a specially prepared,

cylindrical preform which has been locally and symmetrically heated to a temperature range of about 1800°C to about 2200°C. As the preform is heated, such as by feeding the preform into and through a furnace, a glass fiber is drawn from the molten material. The primary and optional secondary coating materials are applied to the glass fiber after it has been drawn from the preform, preferably immediately thereafter. In general, the primary polymeric coating material, in an uncured or liquid form, is applied to the glass fiber, typically by passing the fiber through a pool of the uncured or dissolved primary polymeric coating material. The coating is then cured through ultraviolet light or other means to produce a cured, coated optical fiber. The method of curing the polymeric coating varies depending upon the nature of the initial polymeric material and initiator. It is frequently advantageous to apply both the primary and secondary polymeric coating materials, in sequence or "in-line", during the drawing process. One method of applying dual layers of coating materials to a moving glass fiber is disclosed in U. S. Patent No. 4,474,830 to Taylor, which is hereby incorporated by reference. Another method for applying dual layers of coating materials onto a glass fiber is disclosed in U. S. Patent No. 4,851,165 to Rennell et al., which is hereby incorporated by reference. Similarly, an optional ink coating can be applied through an in-line process.

The optical fiber contained in the optical fiber ribbon of the present invention includes a central core. Figure 1 illustrates a typical single mode optical fiber 100 of the present invention with a central core 101 and surrounding cladding layer 102. The core 101 is typically a doped silica glass having a cylindrical cross section and a diameter ranging from 5 to 10 μm for single mode fibers. The cladding layer 102 is typically glass (e.g., silica) and is generally about 125 μm in diameter.

The single mode optical fiber shown in Figure 1 has a step-index refractive profile. The central core 101 has a refractive index, n_1. The cladding layer 102, which surrounds the central core 101, has a refractive index n_2. The refractive index n_1 is greater than n_2 in order for the optical signal to be propagated across the length of the optical fiber via total internal reflection. One key parameter of the fiber is the fractional change delta in the index of refraction (Δ), which is expressed by the equation, $\Delta = (n_1^2 - n_2^2)/2*n_1^2 \approx (n_1 - n_2)/n_1$. Typical values of Δ for the fibers of the present invention fall within the range of from about 0.2 to about 0.5, more preferably from about 0.3 to 0.4, and even more preferrably from about .32 % to about .4%. Figure 2 shows the

relationship of Δ versus fiber radius for three single mode optical fibers of the present invention and illustrates this range.

The three single mode fibers of the present invention were made by the OVD process. The glass is silica doped with germania in the core to increase the refractive index. The fibers were made with a step-index type profile. In such a profile, the wave guiding properties are influenced by the Δ and core radius, a. The relationship between cutoff wavelength, Δ, a, and V are described above. For V equal to 2.405, the cutoff wavelength is proportional to Δ and core radius, a. Increasing either profile parameter will increase the cutoff wavelength.

The mode field radius or spot size is related to core radius, a, and V by the following equation:

$$\omega_0 \propto a * \left(0.65 + 1.62V^{-1.5} + 2.88V^{-6}\right)$$

where: ω_0 is the spot size

Since V is related to Δ and core radius, a, the mode field radius can be decreased by appropriately designing the step index parameters. A more detailed description of ω_0 is given in Section 4.8.1 of John M. Senior, Optical Fiber Communications: Principles and Practice (1985) and Section 5.4 of Joseph C. Palais, Fiber Optic Communications (1984) which are incorporated in their entirety herein by reference.

Analyses defining the relationship between cutoff wavelength and mode field radius for non-step index profiles would be similar. Such profiles may have additional profile parameters.

The present invention is applicable to single mode fibers which may possess a variety of refractive index profiles. In certain embodiments of the present invention, the core and cladding layer exhibit a discernible core-cladding boundary. These distinctive boundaries can be achieved in one or a series of varying refractive indices. These fibers may possess a ring (higher refractive index) or moat (depressed or lower refractive index) surrounding the central core depending upon the desired optical properties. Still other fibers possess refractive index profiles that may be triangular, W-

shaped or have further distinctions. Alternatively, the core and cladding layers can lack a distinct boundary, such as where the core and cladding, generally both made of glass, are diffused into one another to form a graded index fiber. Because the core layer of these fibers may include one or more refractive indices, it is referred to throughout this discussion as the central core region. Each fiber has a unique electromagnetic mode distribution and their V values at the cut-off wavelength will differ slightly due to their refractive index profile. The present invention is applicable to any single mode optical fiber which has a low MAC number or a lower MFD and a relatively higher cut-off wavelength than standard single mode fiber.

Variations in the refractive index are obtained by adding dopants to layers within the central core region or surrounding cladding area. Optical fiber preforms and waveguides are composed primarily of high purity silica glass. Certain dopants such as the oxides of titanium, thallium, germanium, aluminum and phosphorous are added, in a weight percentage ranging typically from about 1 to 25%, to increase the refractive index of the glass. Other dopants such as oxides of fluorine and boron are added in similar amounts to decrease the refractive index of the glass. In the preferred embodiment, the optical fibers of the present invention are glass fibers with a Ge-doped central core and a SiO_2 cladding. It is understood, however, that the present invention is not limited to this compositional profile.

Figures 3, 4, and 5 compare optical fibers of the present invention against optical fibers of the prior art. The optical fibers used for comparison are prior art fibers referred to herein as Comparative Fiber X. Table 1 provides a comparison of the optical fibers of the present invention and the aforementioned prior art optical fibers and information about their relative properties.

Table I

	Fibers of the Present Invention	Comparative Fiber X
Sample Population	n = 3 fibers	n = 5 fibers
Fiber Cut-off Wavelength (λ_c)	1150 nm – 1500 nm	1300 nm - 1320 nm
Cut-off Wavelength (λ_c) (cabled)	1310 nm maximum	1260 nm or below
Mode Field Diameter (MFD)	8.6 μm at 1310 nm 9.7 μm at 1550 nm	8.8 μm ± 0.5 at 1310 nm 9.7 μm ± 0.6 at 1550 nm
MAC number at 1625 nm	7.6 - 7.8	8.2 and above
Wavelength of Zero Dispersion	1300 nm - 1320 nm	1310 nm - 1320 nm
Micro-bending Loss at 1700 nm (lateral load)	.48 dB/m	.71 dB/m
Macro-bending Loss at 1700 nm (1 mandrel turn @ 20 mm)	5 dB/m	10.9 dB/m
Attenuation Loss at 1700 nm (loose coil)	< 0.5 dB/m	< 0.5 dB/m

The information for the prior art optical fibers are based upon manufacturer's specification information and comparative test measurements.

Microbend loss data is listed in Table I. For the lateral load test used to determine the microbend loss data, each optical fiber was coiled into a circular loop of 98.5 mm diameter, placed into a Instron testing device, and secured upon the Instron platform with 3 mm width tape. The optical fiber was then sandwiched between a rubber pad of hardness shore A 70±5 and a no. 70 woven wire mesh. The initial attenuation for each fiber was recorded at 10 nm wavelength increments beginning at 1300 nm and concluding at 1700 nm. Next, each optical fiber was subjected to a compressive lateral load which was applied in increments of 10 Newtons by bringing the upper plate and lower platform of the Instron device together. The induced attenuation is recorded for each fiber within the sample population at each load point. The load ranged from 0 N to 70 N and was measured at intervals of 10 N. The change in attenuation due to the compressive load was recorded for each fiber in dB/m across the wavelength range. A similar test is described in "Characterization of Bending Sensitivity of Fibers by MAC Number", E. Unger & W. Stocklein, *Optical Communications*, Vol. 107, pages 361 - 364.

The MAC numbers for each fiber within the sample population were calculated

by dividing the MFD at the relevant wavelength (e.g., 1625 nm) by the fiber cut-off wavelength at the relevant wavelength (e.g. 1625 nm) and then multiplying by 1000. Fiber cutoff wavelength for a single mode fiber is measured in accordance with FOTP-170B which is incorporated herein by reference. The optical fibers of the present invention typically have significantly lower MAC numbers, at about 7.8 or about 7.6 and below, when compared to prior art optical fibers. Comparative Fiber X had MAC numbers which ranged from about 8.2 to about 8.6.

Figure 3 illustrates the averaged attenuation or micro-bending loss versus wavelength of various single mode fibers compared against the single mode, optical fiber waveguide of the present invention under lateral load conditions. Averaged attenuation is equal to the attenuation of like fibers within the sample population measured at each wavelength and then averaged together. The lateral load conditions are similar to the test conditions that the optical fibers were subjected to in rendering the data for Table I.

A sample population of three fibers of the present invention and five fibers of Comparative Fibers X of the prior art were measured for attenuation at intervals of 10 nm and the data was averaged and plotted. As Figure 3 illustrates, the average attenuation for the fibers of the present invention range from about 0.31 dB/m at 1550 nm to about 0.48 dB/m at about 1700 nm. Figure 3 also shows the averaged micro-bending loss for Comparative Fiber X of the prior art. Comparative Fiber X exhibited an averaged micro-bending loss from about 0.49 dB/m at 1550 nm to about 0.71 dB/m at about 1700 nm. Clearly, the optical fibers of the present invention exhibit a significantly lower micro-bending loss for this desired wavelength range.

Figure 4 illustrates the average attenuation value of several fibers with similar MAC numbers versus wavelength of various single mode fibers compared against the single mode optical fiber waveguide of the present invention under loose coil conditions. Each fiber sample was loosely wound onto a large (about 18 inch diameter) drum similar to conventional shipping drums used to transport fibers. A length of fiber was cleaved to an end angle of $< 2°$ on both the input and output ends. The fiber length was loaded into a Photon Kinetics 2200 bench (PK5) system and secured in place via couplers. The transmitted intensity was scanned over a wavelength range from 1300 nm to 1700 nm and the measurements were taken every 10 nm. The attenuation in

dB/km was measured for each fiber. The attenuation was then averaged for the present invention and for Comparative Fiber X. Figure 4 shows that the loose coil averaged attenuation for fiber of the present invention and for Comparative Fiber X of the prior art is similar over the wavelength range. This points out that, while the benefit of the present invention exhibited by the fibers of the present invention may not be seen in certain bend tests, the benefit will be seen in bend tests used to predict cabled fiber performance.

Figure 5 illustrates the averaged attenuation value versus wavelength of various single mode fibers compared against the single mode, optical fiber waveguide of the present invention subject to 1 mandrel turn at 20 mm (the macrobend test). This test is typical of actual conditions of a cabled fiber and illustrates the macro-bending loss for these fibers over a range of wavelengths. Each optical fiber was tested in accordance with FOTP-62, Method B and the attenuation results were obtained via a Photon Kinetics 2200 Bench (PK5) System. A test population of three fibers of the present invention and five fibers of Comparative Fiber X were cleaved at both the input and output ends and then placed into the test instrument. Each fiber was wound and supported around the specified mandrel diameter and turns. A minimum tension was then applied to each fiber. The fiber was next scanned for transmitted power every 10 nm increment over the 1300 nm to 1700 nm wavelength range. The fiber was then removed from the mandrel. Next, the fiber was scanned without the mandrel every 10 nm increment over the 1300 nm to 1700 nm wavelength range for reference. The attenuation measured in dB/m was calculated for each fiber. Lastly, the attenuation measurements for each fiber type was averaged and plotted.

Figure 5 illustrates that the fibers of the present invention exhibited a range of average macro-bending loss from about 0.7 dB/m at a wavelength of 1550 nm to slightly less than 5 dB/m at a wavelength of 1700 nm. By comparison, Comparative Fiber X exhibited a bending loss which ranged from about 2.3 dB/m at 1550 nm to about 11 dB/m at a wavelength of 1700 nm. As Figure 5 shows, the optical fibers of the present invention exhibit a significantly lower macro-bending loss at the desired operating wavelength range.

The optical fibers of the present invention can be further incorporated into a ribbon matrix material which maintains the plurality of coated optical fibers in

substantially coplanar alignment. Figure 6 illustrates a plurality of optical fibers of the present invention encased into a ribbon matrix material. Each of the plurality of optical fibers 701 contained within the optical fiber ribbon cable 700 is comprised of a central core 702, a cladding layer 703 surrounding and adjacent to central core 702, and a primary polymer coating layer 704 surrounding and adjacent to the cladding layer 703. The primary polymer coating layer 704 can, optionally, be surrounded by and adjacent to a secondary polymer coating material 705. It is preferred that the secondary coating material 705 generally have a higher tensile modulus relative to the primary coating material 704.

The optical fiber components of the optical fiber ribbon of the present invention can, optionally, also include a coloring material, such as a colored ink coating layer 706 which identifies each optional fiber in the ribbon. Preferably, the optional ink coating layer 706 surrounds and is adjacent to the outermost polymeric coating material, either primary coating layer 704 or secondary coating layer 705. The optical ribbon cable 700 depicted consists of four coated, substantially coplanar optical fibers 701 set in ribbon matrix material 708. The present invention, however, is not limited to a four optical fiber cable or to the cable arrangement depicted. A plurality of coated, substantially coplanar optical fibers 701 can be set within the ribbon matrix material 708. The ribbon matrix material 708 can encapsulate the plurality of optical fibers 701, or, alternatively, the optical fibers 701 can be bonded to each other and then encased within the matrix material 708. The matrix material can be made of a single layer or of a composite construction. Suitable matrix materials include polyvinyl chloride as well as those other materials known to be useful as primary and secondary polymeric coating materials. Preferably, the matrix mixture is the same type of material as that used in the optional secondary coating.

The coated optical fibers are then disposed in a coplanar arrangement and held in this arrangement while an uncured ribbon matrix material is applied and cured. It may be advantageous, in some instances, to initially prepare a plurality of reels of coated optical fibers and then to produce the optical fiber ribbon in a separate process, particularly if the optimum speeds of fiber drawing and coating and ribbon manufacture are significantly different.

A typical UV-curable ribbon matrix material is a mixture comprising a resin, a

diluent, and a photoinitiator. The resin can include a diethylenic-terminated resin synthesized from a reaction of a hydroxy-terminated alkyl acrylate with a reaction product of a polyester of polyether polyol of molecular weight of 1000 to 6000 daltons with an aliphatic or aromatic diisocyanate. Alternatively, the resin can include a diethylenic-terminated resin synthesized from the reaction of glycidol acrylate with a carboxylic-terminated polymer or polyether of molecular weight 1000 to 6000 daltons. The diluent can comprise monofunctional or multifunctional acrylic acid esters having a molecular weight of 100 to 1000 daltons, N-vinyl pyrrolidone, or vinyl caprolactam. Photoinitiators, suitable for use in the ribbon matrix material include ketonic compounds, such as diethoxyacetophenone, acetophenone, benzophenone, benzoin, anthraquinone, and benzyl dimethyl ketal. In a typical composition, the ribbon matrix material can include a resin (50-90 weight %), diluents (5-40 weight %), and a photoinitator (1-10 weight %). Other suitable additives, such as methacrylates, UV-curing epoxides, or unsaturated polyesters, can also be used.

A variety of methods are known in the art for encapsulating the optical fibers in a ribbon matrix material. Briefly, the plurality of coated optical fibers are conducted side-by-side through a liquid ribbon matrix material, which is advantageously delivered under pressure or under vacuum in a coating chamber of substantially rectangular cross section. More detailed information regarding the production of encapsulated optical fiber ribbons is available in U. S. Patent No. 4,752,112 to Mayr and U. S. Patent No. 5,486,378 to Oestreich et al., which are hereby incorporated by reference.

The optical fibers of the present invention can be further incorporated into an optical fiber transmission system that can transfer information at an operating wavelength range higher than that typically encountered in the prior art. Figure 7 illustrates a typical optical fiber transmission system 800; it being understood that the present invention is not limited to the system depicted. The optical fiber transmission system 800 generally consists of the signal to be transmitted 801, a source 802, a modulator 803, the optical fiber cable link 804, connectors 805, splices 806, and signal amplifier 807. The signal to be transmitted 801 can be digital or analog, but preferably is digital. The source 802 for the optical signal can be a LED, laser or any other light emitting source. For the present invention, source 802 should be capable of generating higher operating wavelengths of around 1550 nm or above. The source 802 is passed

through a modulator 803 where the electrical energy of the original signal 801 is converted into an optical signal. This optical signal is then transmitted through the length of the optical fiber link 804.

The optical fiber link 804 consists of and includes a transmitter, detector and fiber cable assembly that allows the optical signal to be transmitted across two points. The optical fiber link 804 has connectors 805 attached to the source 802 and a detector. A detector is a device that provides an electrical output signal in response to an incident optical signal. The current emitted by the detector is dependent upon the amount of light received and the type of device.

As Figure 7 depicts, the optical fiber link 804 can be connected in series with additional fiber links as shown. Connectors 805 are mechanical devices that are used to align and join optical fiber links together and/or provide a means for attaching and decoupling it to a transmitter, receiver, or other fiber. Splices 806 are permanent joints which connect two optical fiber links 804. The system 800 may further include signal repeaters 807 and amplifiers. Repeaters 807, which consists of a transmitter and a receiver or transceiver, are used to regenerate a signal to increase the system length. Amplifiers are devices that amplify the strength of an electronic signal. In a typical optical system, amplifiers are spaced at regular intervals throughout the system to keep the signal propagated along the cable length. The present invention allows the optical signal to be transmitted at a greater distances without requiring the need for optical signal enhancement, due to lower attenuation in the higher wavelength ranges. For example, the distance between said optical amplifiers within the system can be extended up to 150 km. This lessens the number of optical amplifiers within the overall system and lowers total system costs.

The optical fiber system can further include a WDM system 808. The WDM is further illustrated in the subsequent drawing, Figure 8. Lastly, the optical fiber links 804 are connected into a receiver 809 device. The receiver device 809 converts the optical signal which was transmitted from the series of fiber links into an electrical signal.

Single mode optical fibers are particularly suited for a transmission system known as WDM systems. The optical fibers of the present invention can be also be incorporated into a WDM system. Figure 8 illustrates a simple four-channel WDM

system 900; it being understood that the present invention is not limited to the system depicted. WDM systems are high data rate systems that allow simultaneous transmission of several signals in an optical waveguide at differing wavelengths. These systems usually include a source (such as a laser or other means) that can send signals at multiple wavelengths or input channels 901 through 904, a multiplexing unit 905, an optical fiber cable link 906, a de-multiplexing unit 907, and multiple output sources or output channels 908 through 911.

U.S. Pat. No. 5,483,612, issued to Gallagher et al., assigned to the owner of the present invention, and incorporated herein by reference, discloses a typical WDM system of the present art. Present WDM systems separate the wavelengths of the input channels by about 1 - 10 nm. Finer wavelength separations can allow for more optical signals to be transmitted along the length of the optical fiber but can also create cross-talk problems. Additionally, single mode optical fibers of the prior art are ill-suited to meet the demands of a WDM system due to the difficulties in minimizing total dispersion and attenuation loss, particularly in the higher wavelength ranges.

The multiplexing unit 905 receives the four signals from the input channels 901 through 904 and then combines them for transmission over a single communications channel or optical fiber link 906. The de-multiplexing unit 907 receives the single signal from the optical fiber link 905 and then separates the optical signal into the individual output channels, 908 through 911.

While the present invention has been particularly shown and described with reference to the presently preferred embodiments thereof, it will be understood by those skilled in the art that the invention is not limited to the embodiments specifically disclosed herein. Those skilled in the art will appreciate that various changes and adaptations of the present invention may be made in the form and details of these embodiments without departing from the true spirit and scope of the invention as defined by the following claims.

We claim:

1. A single mode optical fiber capable of operating in wavelengths between about 1300 nm and about 1700 nm with minimal loss, said fiber comprising: a MAC number, measured at 1625 nm, equal to or less than about 7.8.

2. The single mode optical fiber of claim 1 wherein said mode field diameter is 8.6 Fm or less at a wavelength of 1310 nm.

3. The single mode optical fiber of claim 1 further comprising a cabled cut-off wavelength is at most about 1330 nm.

4. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to micro-bending is less than 0.7 dB/m at 1700 nm.

5. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to micro-bending is less than 0.48 dB/m at 1700 nm.

6. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to micro-bending is less than 0.49 dB/m at 1550 nm.

7. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to micro-bending is less than 0.35 dB/m at 1550 nm.

8. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to macro-bending is less than 11 dB/m at 1700 nm.

9. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to macro-bending is less than 5 dB/m at 1700 nm.

10. The single mode optical fiber of claim 1 wherein said loss of said single mode optical fiber attributable to macro-bending is less than 2 dB/m at 1550 nm.

11. The single mode optical fiber of claim 1 said loss of said single mode optical fiber attributable to macro-bending is less than 0.7 dB/m at 1550 nm.

12. A single mode optical fiber, capable of operating in a wavelength range between about 1300 nm and about 1700 nm while minimizing micro-bending and macro-bending induced attenuation, said fiber comprising:

a central core region with a maximum refractive index n_1;

a cladding layer, adjacent to and surrounding said central core region, having refractive index n_2, which is less than said refractive index n_1, the relative differences between said refractive indices being delta ()); and

wherein said single mode optical fiber has a MAC number of about 7.8 or less at a wavelength of 1625 nm.

13. The single mode optical fiber of claim 12 wherein said MAC number is about 7.6 or less at a wavelength of 1625 nm.

14. The single mode optical fiber of claim 12 wherein said mode field diameter is equal to or less than 8.6 Fm at a wavelength of 1310 nm..

15. The single mode optical fiber of claim 12 wherein said fiber comprises a fiber cut-off wavelength greater than 1330.

16. The single mode optical fiber of claim 12 wherein said delta ()) is between about 0.3% and about .4%.

17. The single mode optical fiber of claim 12 wherein said micro-bending loss of said single mode optical fiber is less than 0.7 dB/m at 1700 nm.

18. The single mode optical fiber of claim 12 wherein said micro-bending loss of said single mode optical fiber is less than 0.48 dB/m at 1700 nm.

19. The single mode optical fiber of claim 12 wherein said micro-bending loss of

said single mode optical fiber is less than 0.49 dB/m at 1550 nm.

20. The single mode optical fiber of claim 12 wherein said micro-bending loss of said single mode optical fiber is less than 0.35 dB/m at 1550 nm.

21. The single mode optical fiber of claim 12 wherein said macro-bending loss of said single mode optical fiber is less than 11 dB/m at 1700 nm.

22. The single mode optical fiber of claim 12 wherein said macro-bending loss of said single mode optical fiber is less than 5 dB/m at 1700 nm.

23. The single mode optical fiber of claim 12 wherein said macro-bending loss of said single mode optical fiber is less than 2 dB/m at 1550 nm.

24. The single mode optical fiber of claim 12 wherein said macro-bending loss of said single mode optical fiber is less than 0.7 dB/m at 1550 nm.

25. An optical fiber ribbon cable comprising an optical fiber in accordance with claim 1.

26. An wavelength-division multiplexing ("WDM") system comprising:

at least one optical signal source modulated at different wavelengths within the region of about 1300 nm to about 1700 nm;

an apparatus for modulating the optical signals at the input of said WDM system;

an apparatus for demultiplexing the optical signals at the output of said WDM system; and

a transmission path which extends between said multiplexing apparatus and said demultiplexing apparatus, said transmission path comprising a cabled optical fiber, said optical fiber having a cabled cut-off wavelength of at most about 1310 nm, a mode field diameter of equal to or less than 8.6 Fm at a wavelength of 1310 nm, and a MAC number of about 7.8 or less at a wavelength of 1625 nm and comprising a central core region with a

maximum refractive index n_1 and a cladding layer, adjacent to and surrounding said central core region, having a refractive index n_2 which is less than said refractive index n_1.

27. The WDM system of claim 26 wherein said transmission path further comprises at least one optical amplifier.

28. The WDM system of claim 26 wherein said transmission path further comprises at least two optical amplifiers, spaced apart by between 40 and 150 meters.

29. The WDM system of claim 26 wherein said plural sources of optical signals are laser sources.

30. An optical fiber network comprising:

a source that converts an electrical signal into an optical signal at wavelengths of about 1300 nm to about 1700 nm;

a transmission medium comprising an optical fiber ribbon cable, said optical fiber ribbon cable comprising a plurality of optical fibers; each of said cabled optical fibers having a cut-off wavelength of at most about 1310 nm, a mode field diameter of 8.6 Fm or less at a wavelength of 1310 nm, and a MAC number of about 7.8 or less at a wavelength of 1625 nm; and

a receiver which is capable of converting said optical signal into said electrical signal.

31. The optical fiber network of claim 30 wherein said transmission medium further comprises at least one optical amplifier.

32. The optical fiber network of claim 30 said transmission medium comprises at least two optical amplifiers, spaced apart by between 40 and 150 km.

FIG. 1

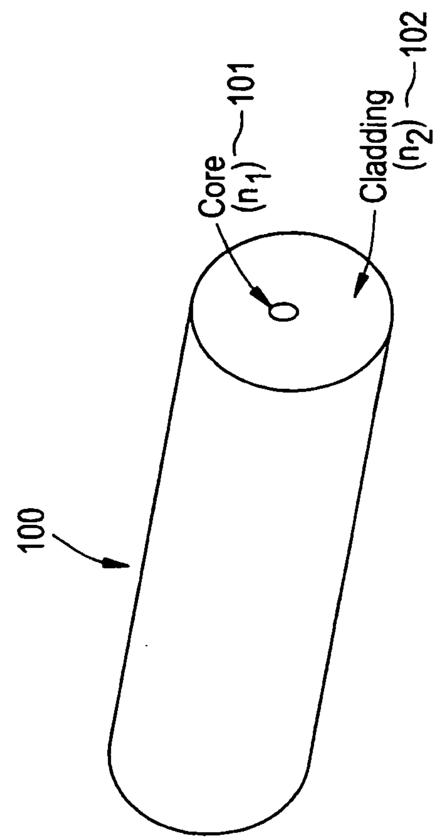


FIG. 2

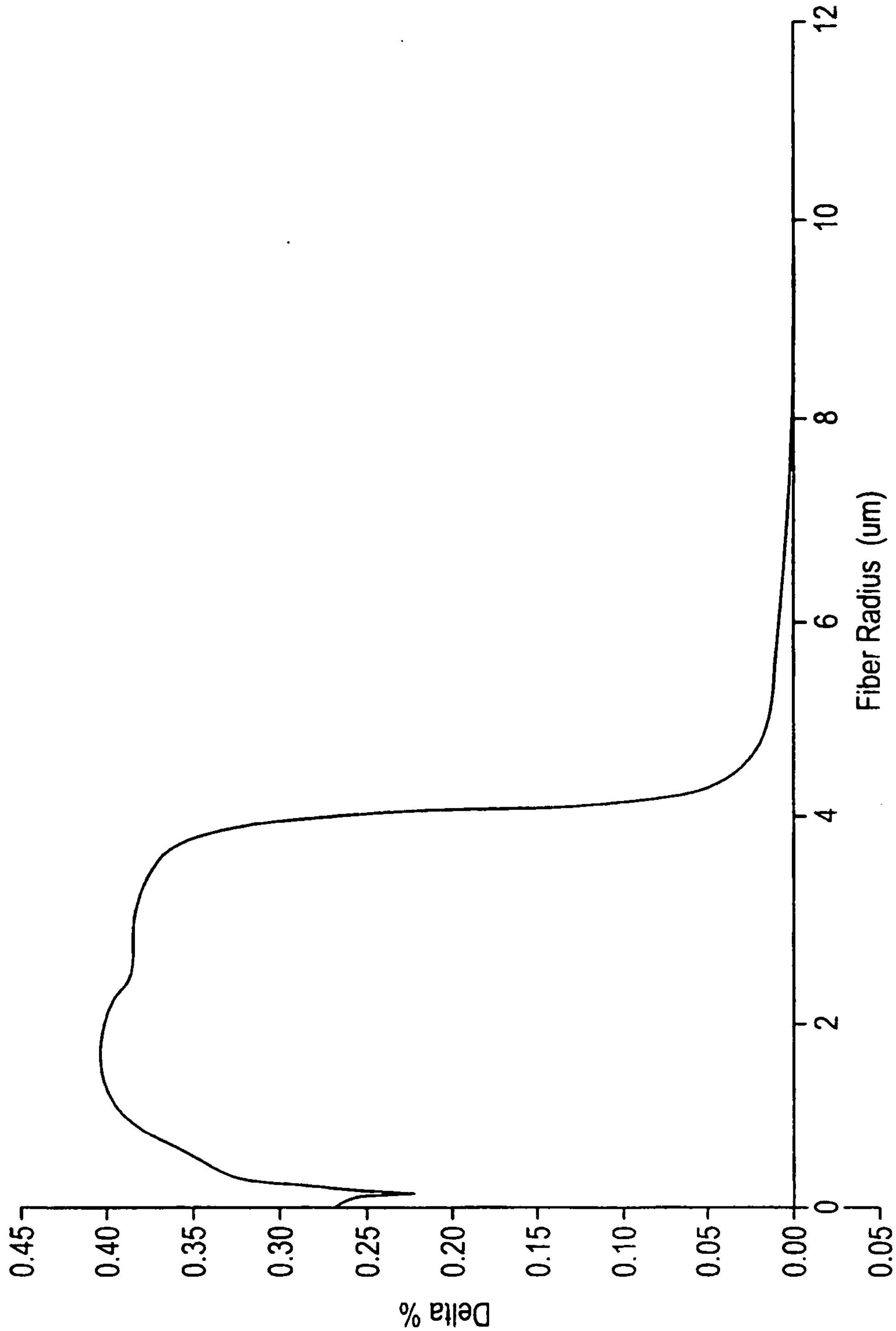
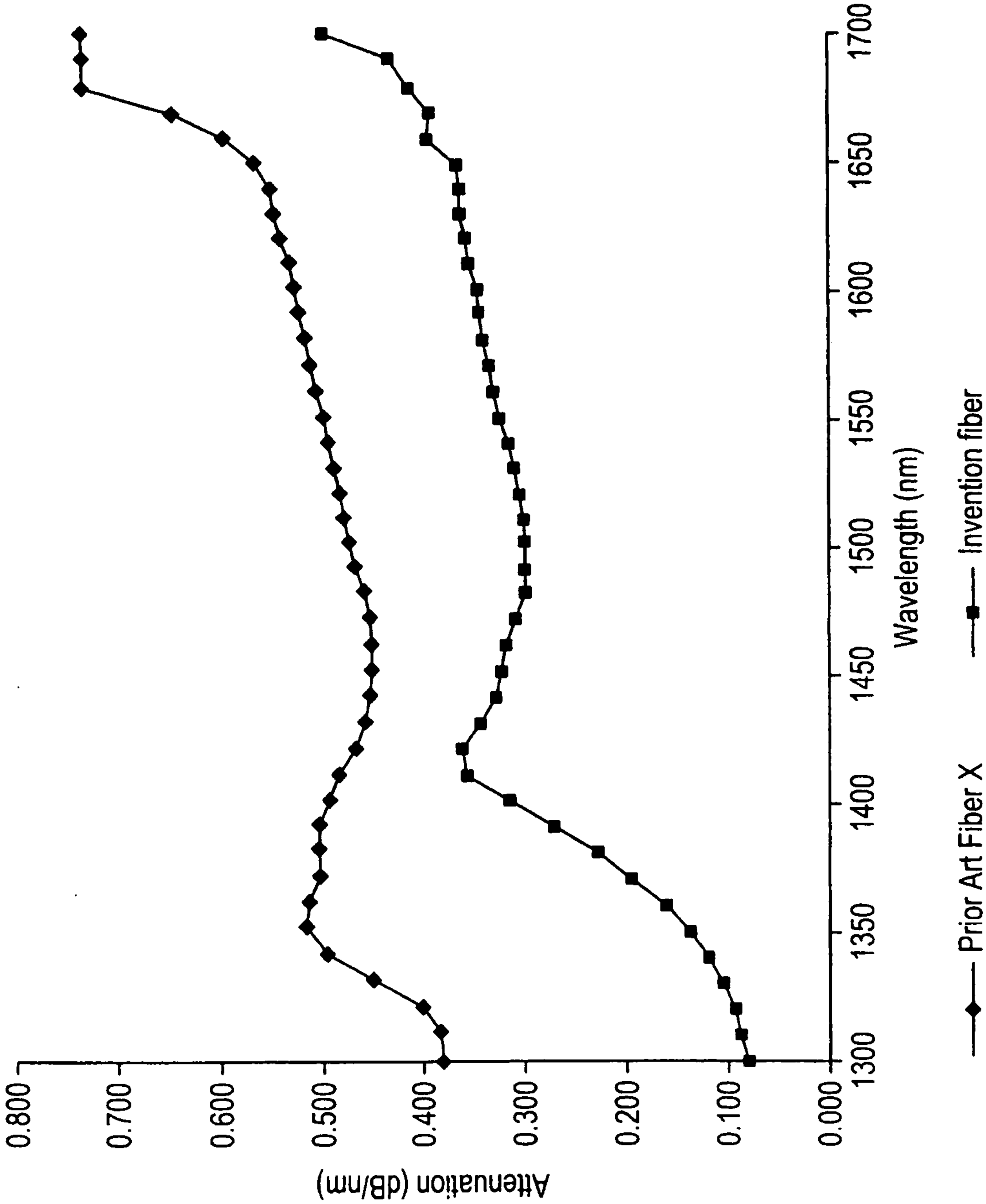

Delta %
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.05
0
2
4
6
8
10
12
Fiber Radius (um)

FIG. 3


Attenuation (dB/nm)
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0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1300
1350
1400
1450
1500
1550
1600
1650
1700
Wavelength (nm)
Prior Art Fiber X
Invention fiber

FIG. 4

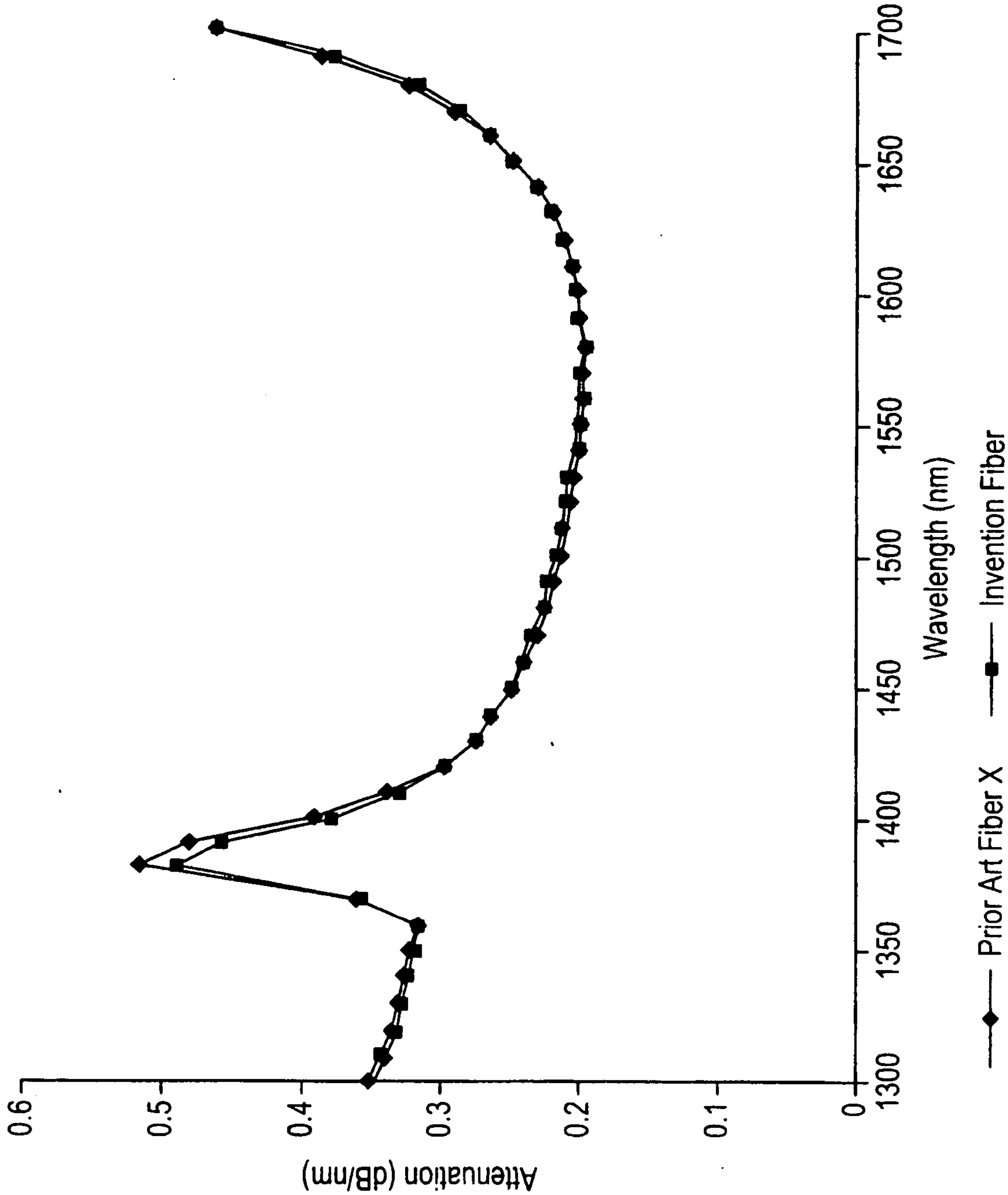

Attenuation (dB/nm)
0.6
0.5
0.4
0.3
0.2
0.1
0
1300
1350
1400
1450
1500
1550
1600
1650
1700
Wavelength (nm)
Prior Art Fiber X
Invention Fiber

FIG. 5

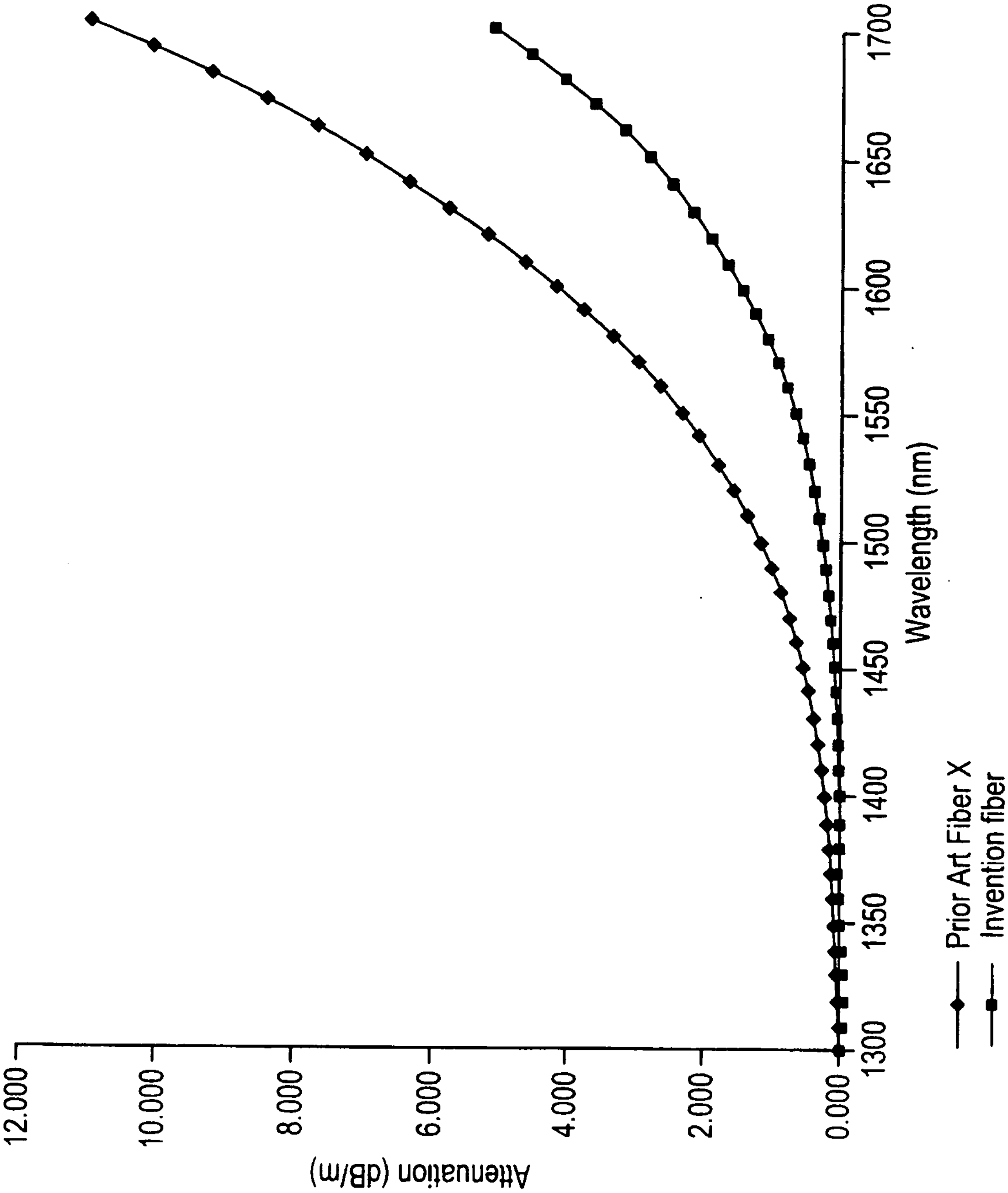

Attenuation (dB/m)
12.000
10.000
8.000
6.000
4.000
2.000
0.000
1300
1350
1400
1450
1500
1550
1600
1650
1700
Wavelength (nm)
Prior Art Fiber X
Invention fiber

FIG. 6

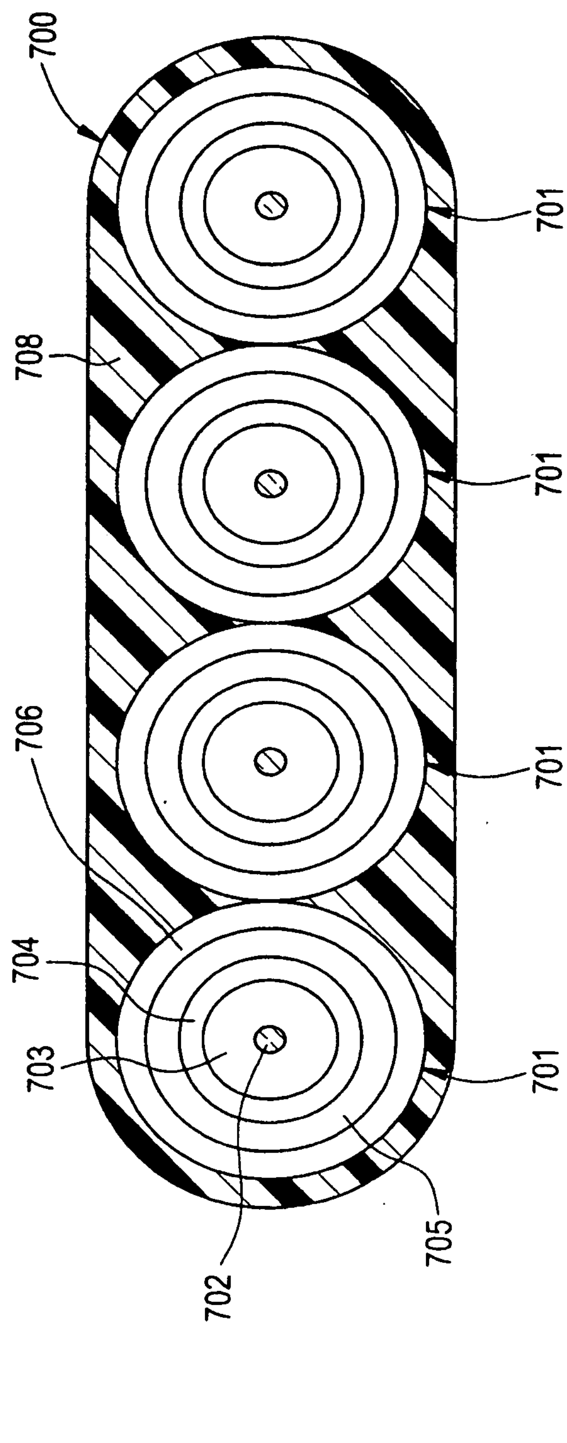


FIG. 7

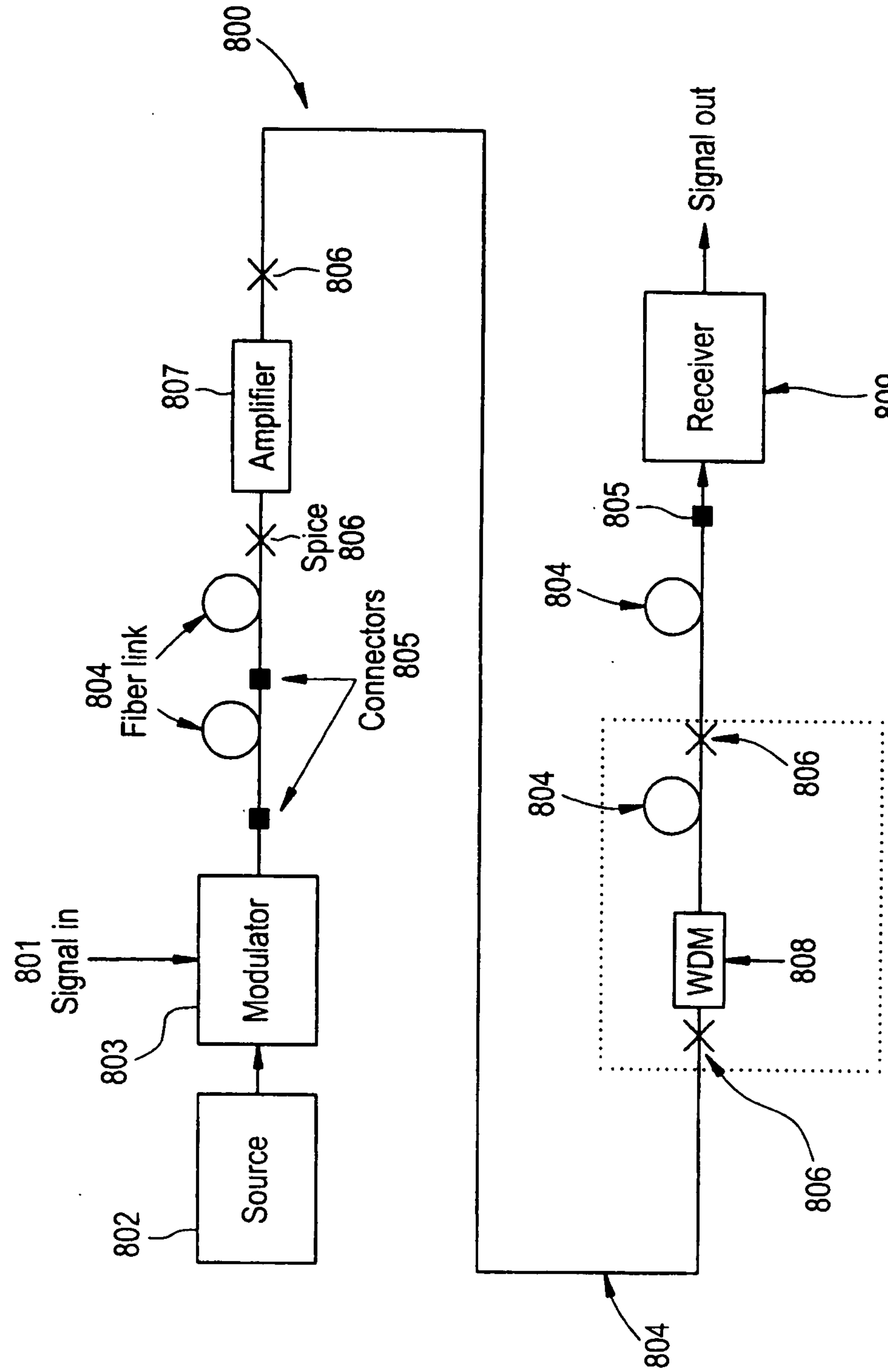
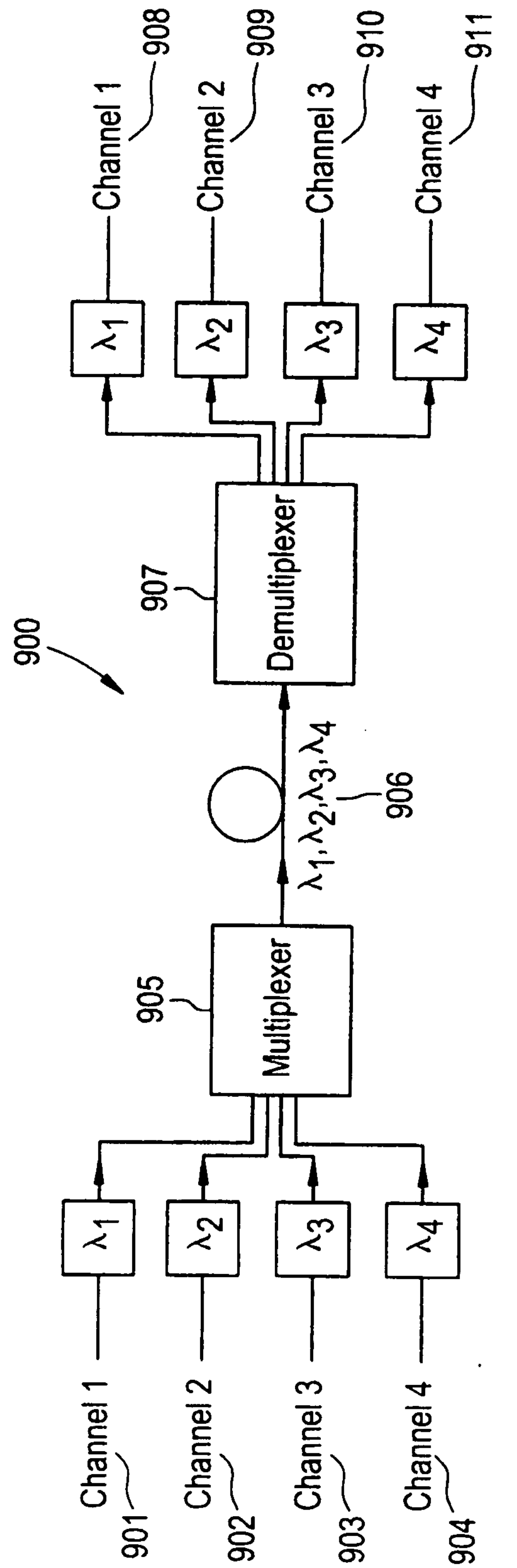

800
Source
802
Modulator
803
801
Signal in
804
Fiber link
Connectors
805
Spice
806
Amplifier
807
806
804
WDM
808
806
806
804
804
805
Receiver
809
Signal out

FIG. 8


900
Channel 1
Channel 2
Channel 3
Channel 4
901
902
903
904
λ_1
λ_2
λ_3
λ_4
Multiplexer
905
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$
906
Demultiplexer
907
λ_1
λ_2
λ_3
λ_4
Channel 1
Channel 2
Channel 3
Channel 4
908
909
910
911